

Molecules in η Carinae

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ABSTRACT

We report the detection toward η Carinae of six new molecules, CO, CN, HCO⁺, HCN, HNC, and N₂H⁺, and of two of their less abundant isotopic counterparts, ¹³CO and H¹³CN. The line profiles are moderately broad ($\sim 100 \text{ km s}^{-1}$) indicating that the emission originates in the dense, possibly clumpy, central arcsecond of the Homunculus Nebula. Contrary to previous claims, CO and HCO⁺ do not appear to be under-abundant in η Carinae. On the other hand, molecules containing nitrogen or the ¹³C isotope of carbon are overabundant by about one order of magnitude. This demonstrates that, together with the dust responsible for the dimming of η Carinae following the Great Eruption, the molecules detected here must have formed *in situ* out of CNO-processed stellar material.

Subject headings: Astrochemistry — ISM: molecules — circumstellar matter — stars: chemically peculiar — stars: mass-loss — stars: winds, outflows

1. Introduction

η Carinae is well known to have experienced a major outburst in the 1840s, during which it became the second brightest star in the entire sky (e.g., Humphreys & Davidson 1999). Known as the *Great Eruption*, this outburst was associated with an episode of extreme mass-loss (about

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10 M_{\odot} of material was expelled in about 20 years) that resulted in the creation of the bipolar-shaped *Homunculus Nebula* whose current size is about $16'' \times 10''$, or 0.18×0.11 pc assuming a distance of 2.3 kpc (Walborn 1995, Allen & Hillier 1993). Over the following decades, the visual brightness of η Carinae faded by many magnitudes, but early infrared observations by Neugebauer & Westphal (1968) revealed that the bolometric luminosity in the second half of the 20th century remained comparable to that during the Great Eruption. The dimming at optical wavelengths resulted from obscuration by dust particles, presumably formed *in situ* out of the ejected material.

A scant handful of molecular species have been detected toward η Carinae. Molecular hydrogen, traced by its 2.12 μm line, appears to be distributed over the outer surface of the Homunculus Nebula, and is strongest towards the polar caps where the intercepted column is largest (Smith 2002; 2006). Two other simple diatomic molecules (CH and OH) were identified in Hubble Space Telescope STIS spectra through their UV absorption lines (Verner et al. 2005). Both also originate in the thin outer layer of the Homunculus. Finally, radio emission from ammonia (NH_3) was detected by Smith et al. (2006) using the Australia Telescope Compact Array (ATCA). The ammonia emission is confined to a region roughly 1 arcsec across, and shares the kinematics of the H_2 2.12 μm line in the same region.

Interestingly, carbon monoxide (CO) has never been detected toward η Carinae in spite of sensitive searches at millimeter, infrared, and UV wavelengths (Cox & Bronfman 1995; Smith 2002; Verner et al. 2005). As discussed by Smith et al. (2006), this lack of CO detection could reflect the C/O depletion and N enrichment of the material ejected during the Great Eruption. Indeed, the ionized gas surrounding the Homunculus nebula is known to be composed of such nitrogen-rich CNO-processed material (Davidson et al. 1982; Davidson et al. 1986; Dufour et al. 1997; Hillier et al. 2001; Smith & Morse 2004). In addition, the abundance of the nitrogen-bearing ammonia molecule in the Homunculus itself is estimated to be about 2×10^{-7} , roughly one order of magnitude higher than in cold interstellar clouds (Smith et al. 2006). It should be emphasized, however, that the existing, unsuccessful, searches for CO in η Carinae are insufficient to place meaningful limits on the $[\text{CO}]/[\text{NH}_3]$ abundance ratio in the Homunculus (Smith et al. 2006). Thus, the low abundance of carbon monoxide in η Carinae is still not firmly established.

The formation and survival of molecules in the harsh environment of η Carinae, within 1'' (0.01 pc) of a 100 M_{\odot} star, remain poorly understood. Other classes of massive stars (such as red supergiants and Wolf-Rayet stars) are known to be surrounded by significant quantities of molecular gas, although at greater distances, which might indicate that it represents swept-up ambient interstellar material (Pulliam et al. 2011; Cappa et al. 2001; Rizzo et al. 2001, 2003). It is unclear whether or not there is relation between the mechanisms at work in these objects and those occurring in the Homunculus. To tackle these issues, it is important to characterize the molecular content of the Homunculus, and to determine the physical properties and spatial distribution of

the molecular gas. In this *Letter*, we present new sub-millimeter spectroscopic observations of η Carinae designed to search for several new molecular species, including carbon monoxide.

2. Observations

The observations were performed in 2011 October 12–17 and December 15–20 with the Atacama Pathfinder EXperiment telescope (APEX; Güsten et al. 2006) located at an altitude of 5100-m on Llano Chajnantor, Chile. The molecular transitions targeted are listed in Table 1. Two different receivers were used: a modified version of the First Light Apex Sub-millimeter Heterodyne receiver (FLASH; Heyminck et al. 2006) for transitions in the 345 and 460 GHz bands, and the Carbon Heterodyne Array of the MPIfR (CHAMP+; Güsten et al. 2008) for transitions in the 690 GHz band. While FLASH is a single-beam receiver, CHAMP+ provides spectra simultaneously at 7 positions. Those positions correspond to the central (directly on-source) pixel and to 6 lateral points distributed in a hexagonal pattern around the central pixel and separated from it by about $19''$ (Güsten et al. 2008). The Fast Fourier Transform spectrometer backends provided 32,768 frequency channels, each 76.308 kHz wide during the FLASH observations, and 8,192 channels, each 183.1 kHz wide during the CHAMP+ observations. This yields velocity resolutions of 0.07–0.08 km s^{−1} at all frequencies, but the spectra were Hanning-smoothed to 4–5 km s^{−1} during post-processing to improve their signal to noise ratio.

The observations were obtained in ON-OFF position switching mode, with the OFF position at $\alpha_{J2000.0} = 10^{\text{h}}48^{\text{m}}28^{\text{s}}.0$, $\delta_{J2000.0} = -59^{\text{h}}25^{\text{m}}45^{\text{s}}.0$. This position is known to be devoid of molecular emission. Calibration and pointing scans were interspersed with the science spectra throughout the observations. The weather conditions and overall system performance were excellent, and the resulting spectra of very good quality. As a consequence, very few scans had to be discarded, and only low-order polynomial baselines had to be removed. In some cases, oscillatory patterns were present in the spectra, and were removed in the Fourier domain. The intensity scale was converted from T_A^* to T_{mb} using the efficiencies listed in Table 1. We estimate the final flux calibration to be accurate to 15%.

3. Results and Analysis

All the targeted lines were detected toward the source (Figure 1), but no emission was seen in the lateral pixels of the CHAMP+ observations. This demonstrates that the molecular emission is confined to the Homunculus itself. In addition, the line profiles are quite broad (up to about 300 km s^{−1} full width at zero point, with “cores” of roughly 100 km s^{−1} full width at half maximum;

Table 1: Observing log and results

Transition	ν (MHz)	Rx	θ_{mb}^a ($''$)	η_{mb}^b	W^c (K km s $^{-1}$)
CO(3-2)	345795.9899	FLASH	17.5	0.73	24.0 ± 3.6
CO(4-3)	460148.8125	FLASH	13.3	0.60	31.8 ± 4.8
CO(6-5)	691473.0763	CHAMP+	9.0	0.48	73.5 ± 11.0
$^{13}\text{CO}(3-2)$	330587.9653	FLASH	17.5	0.73	7.4 ± 1.1
$^{13}\text{CO}(6-5)$	661067.2766	CHAMP+	9.0	0.48	20.9 ± 3.1
CN(3-2) ^d	340247.7700	FLASH	17.5	0.73	3.7 ± 0.6
HCO $^+(4-3)$	356734.2230	FLASH	17.5	0.73	10.1 ± 1.5
HCN(4-3)	354505.4773	FLASH	17.5	0.73	10.7 ± 1.6
H $^{13}\text{CN}(4-3)$	345339.7694	FLASH	17.5	0.73	8.3 ± 1.2
HNC(4-3)	362630.3030	FLASH	17.5	0.73	7.0 ± 1.0
N $_2\text{H}^+(4-3)$	372672.4645	FLASH	17.5	0.73	24.5 ± 3.7

^a θ_{mb} is the beam size at each frequency.

^b η_{mb} is the main beam efficiency, used to convert the measured antenna temperatures to main beam temperatures.

^c The values reported in this column were obtained by integrating over the entire velocity range where emission is detected: $W = \int T_{mb} d\nu$.

^d CN(3-2) was not specifically targeted, but happened to be detected near the edge of one of the observed bands. As a consequence, only about half of the hyperfine components were included in the band (see Figure 1), and this observation will have to be repeated in the future.

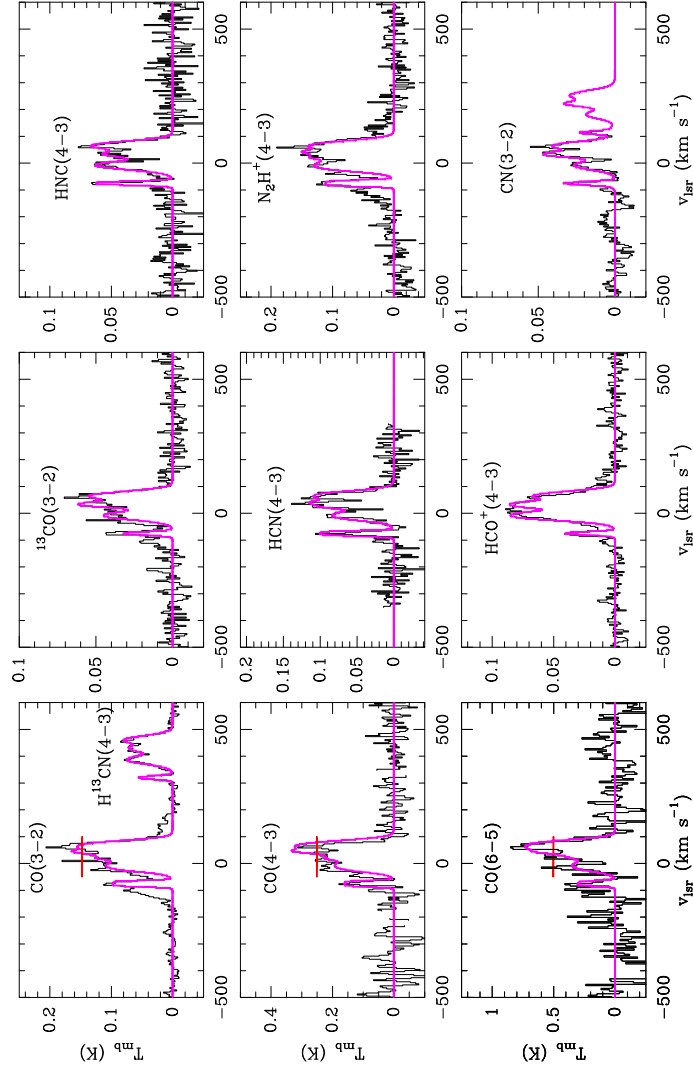


Fig. 1.— Observed spectra towards η Carinae. The magenta curves show the theoretical spectra expected in the conditions described in the text. The horizontal red lines in the three spectra of the left column indicate the typical intensity of the CO lines mentioned in Section 3. The CN line was on the edge of the band and the corresponding profile misses some hyperfine components.

Figure 1) and reminiscent of the NH_3 spectra presented by Smith et al. (2006). In comparison, the Homunculus has expansion velocities of roughly 600 km s^{-1} , while the Weigelt knots near the star have outward velocities less than 50 km s^{-1} (e.g. Hofmann & Weigelt 1988; Weigelt et al. 1995; Davidson et al. 1995). The similarity between the NH_3 spectra (Smith et al. 2006) and those reported here likely indicates that the emission originates in the central few arcseconds of the Homunculus. The emission is centered at $V_{lsr} \sim +20 \text{ km s}^{-1}$, a value somewhat more positive than the systemic velocity of η Carinae (-20 km s^{-1} ; Davidson et al. 1997; Smith 2004).

This is, again, similar to the situation with ammonia (Smith et al. 2006). The observed profiles are clearly not gaussian. Instead, they exhibit significant sub-structure suggesting that the emission might come from a clumpy material. Indeed, all of our spectra are consistent with four velocity components at $v_{lsr} = -76.2, -8.9, +30.5$, and $+63.5$ km s⁻¹. Particularly noteworthy is the narrow component at $v_{lsr} = -76.2$ km s⁻¹ seen in most of our spectra, and most likely associated with the strong H₂ 1-0 S(1) emission detected by Smith (2004; see also Smith et al. 2006) at the same radial velocity.¹

The combination of observed CO and ¹³CO spectra can be used to constrain the physical conditions of the emitting material. First, we note that the relative peak intensities of the CO 3→2, 4→3, and 6→5 lines (0.15, 0.25, and 0.5 K; see the red marks on Figure 1) are almost exactly in the inverse proportion of the corresponding beam areas ($1 \div 1.7 \div 3.8$). This shows that the CO lines are optically thick, and come from a region smaller than all the beams (even that at 690 GHz). For such optically thick lines, there is a degeneracy between temperature and filling factor. This degeneracy can be removed using the ¹³CO line intensities, and we find that all the CO and ¹³CO lines can be reproduced for an excitation temperature of order 70 K and a source size of order 1''. A higher excitation temperature (of, say, 200 K) could reproduce the CO lines provided the source size were 0.5'', but would predict a ¹³CO(6-5)/¹³CO(3-2) line ratio of about 8.5, inconsistent with the observed value of 5. Given the similarities between all the spectra observed here (Figure 1), it is reasonable to assume that all the molecular emission comes from the same material, so we conclude that all the lines reported here originate in a source about 1'' in size where the gas is at a temperature of order 70 K.

To estimate the molecular column densities, we used the myXCLASS program² (see Comito et al. 2005 and references therein), and modeled the emission as a superposition of the four distinct velocity components identified earlier. We used line widths for each component consistent with the observed widths of the optically thin lines ($\Delta v = 13.2, 35.8, 21.6$, and 36.4 km s⁻¹, respectively for the four velocity components), and found reasonable fits to all the lines for excitation temperatures of 40, 50, 40, and 90 K, respectively for the four components. Our approach to column density determinations entails a number of approximations. First, the calculations are made under the assumption of local thermodynamic equilibrium (LTE). To check that this did not strongly affect our results, we used the publicly available non-LTE radiative transfer code RADEX (van der Tak et al. 2007) to verify that the excitation conditions were consistent with LTE. Secondly, our calculations do not consider the opacity due to possible spatial overlap between different velocity components.

¹Note that our spectra are measured in the LSR rest frame, whereas those in Smith (2002, 2004) and Smith et al. (2006) are reported in the Heliocentric system. For η Carinae, $v_{Hel} \approx v_{lsr} + 12$ km s⁻¹.)

²<http://www.astro.uni-koeln.de/projects/schilke/XCLASS>

To decide to which extent this problem might affect our conclusions, high angular resolution observations will be necessary. The column densities resulting from our analysis are given for each species in Table 2, and the corresponding model spectra are shown in Figure 1. We note that the CO column density itself is somewhat uncertain due to its substantial opacity.

The abundance of each species was calculated relative to CO and to molecular hydrogen, assuming a column density $N(\text{H}_2) = 3 \times 10^{22} \text{ cm}^{-2}$ as estimated to be appropriate for this part of the Homunculus by Smith et al. (2006). We note, however, that a somewhat larger column density of H_2 might also be plausible. Based on sub-millimeter and far-infrared observations, Gomez et al. (2010) recently determined the mass of dust surrounding η Carinae to be about $0.4 M_\odot$. For a standard gas-to-dust ratio of 100, this would yield an *average* H_2 column density of about $2 \times 10^{23} \text{ cm}^{-2}$. If the dust distribution were clumpy, however, the column density appropriate for the individual clumps might be several times larger, and the abundances quoted in Table 2 could be proportionately lower.

4. Discussion

Within its uncertainty, the abundance of CO derived here for η Carinae is similar to its canonical interstellar value of 10^{-4} . It is also similar to the typical CO abundances found in O-rich circumstellar envelopes (Ziurys et al. 2009). Thus, CO does not appear to be under-abundant in the Homunculus Nebula, contrary to previous claims based on unsuccessful CO searches. The abundance of HCO^+ is similar to its value in dense massive cores ($\sim 2 \times 10^{-8}$; Vasyunina et al. 2011) and in the dense envelopes surrounding low-mass stars ($\sim 1.2 \times 10^{-8}$; Hogerheijde et al. 1997). It is also in the mid-range of observed abundances in evolved stars with oxygen-rich circumstellar envelopes ($0.5\text{--}13 \times 10^{-8}$; Pulliam et al. 2011), but significantly larger than the abundance in carbon-rich stars, such as IRC+10216 (where it is 4×10^{-9} ; Pulliam et al. 2011). We conclude that both CO and HCO^+ have roughly standard abundances in the Homunculus.

The nitrogen-bearing molecules, on the other hand, are found to be highly over-abundant in η Carinae. While the average abundance of HCN and HNC in low- and high-mass dense cores is $2\text{--}7 \times 10^{-9}$ (Vasyunina et al. 2011), their abundances in η Carinae are $0.7\text{--}2 \times 10^{-7}$ (Table 2). Similarly, the abundance of N_2H^+ is about two orders of magnitude higher in the Homunculus than in dense cores (where it is, on average, 2×10^{-9} ; Vasyunina et al. 2011). The situation is much the same for ammonia (Smith et al. 2006) showing that nitrogen-bearing molecules are consistently one order of magnitude more abundant in the Homunculus than in the dense interstellar medium. Although chemical effects might affect the abundance of specific individual molecules, this combination of results suggests that the abundance of nitrogen itself must be enhanced by one order of magnitude in the Homunculus. The comparison between the abundances of N-bearing

Table 2: Estimated column densities and abundances

Species	N (cm ⁻²)	N/N(H ₂) ^a	N/N(CO)
CO	6.5×10^{18}	2.2×10^{-4}	1
¹³ CO	1.4×10^{18}	4.7×10^{-5}	2.2×10^{-1}
CN	9.0×10^{15}	3.0×10^{-7}	1.4×10^{-3}
HCO ⁺	1.7×10^{15}	5.7×10^{-8}	2.6×10^{-4}
HCN	5.5×10^{15}	1.8×10^{-7}	8.5×10^{-4}
H ¹³ CN	3.1×10^{15}	1.0×10^{-7}	4.8×10^{-4}
HNC	2.1×10^{15}	7.0×10^{-8}	3.2×10^{-4}
N ₂ H ⁺	6.1×10^{15}	2.0×10^{-7}	9.4×10^{-4}

^aAbundance of each species relative to H₂, assuming N(H₂) = 3×10^{22} cm⁻² (Smith et al. (2006)).

species in η Carinae and those in O-rich circumstellar envelopes is somewhat confusing. While HCN is about one order of magnitude less abundant in η Carinae than in O-rich envelopes, the abundance of HNC is similar in both kinds of objects. As a consequence, the [HCN]/[HNC] ratio in η Carinae is of the order of a few, similar to its value, of order unity, in quiescent interstellar cores (Padovani et al. 2011), but very different from its value (a few hundred) in oxygen-rich envelopes (Ziurys et al. 2009). CN, on the other hand, is about one order of magnitude more abundant in η Carinae than in O-rich envelopes (Ziurys et al. 2009).

An important conclusion of our observations concerns the relative abundance of isotopic forms of carbon. The [HCN]/[H¹³CN] ratio is estimated to be about 2, while the [CO]/[¹³CO] ratio is of order 5. This is much smaller than the interstellar ¹²C/¹³C isotopic ratio at the galactocentric radius of η Carinae (~ 70 ; Milam et al. 2005). On the other hand, such a low value of the ¹²C/¹³C is an expected result of the CNO cycle. In particular, for the CNO cycle at a temperature of 10⁸ K, the expected equilibrium value of the ¹²C/¹³C ratio is of order 4 (Rose 1998, Chap. 6), in very good agreement with the isotopic ratio measured here. The high abundance of nitrogen in the ionized gas surrounding the Homunculus (Smith & Morse 2004) and in the Homunculus itself (as documented above) are also expected consequences of the CNO process. Thus, the molecular observations presented here strongly support the idea that the material expelled during the Great Eruption is CNO-processed stellar matter.

We mentioned in the Introduction that dust grains must have formed out of the material ejected by η Carinae during the Great Eruption. The present results demonstrate that large quantities of molecular material have also formed out of this material. It will be interesting to analyze the chemistry that led to the formation of these molecules from the theoretical standpoint, because the elemental composition of the gas (particularly the N and ¹³C enrichment) and the physical

conditions (especially the strong UV field) are very different from those in the interstellar gas. Additionally, the chemistry at play occurred in just a few decades. From the observational point of view, it will be important to further characterize the molecular content of η Carinae. Searching for additional nitrogen-bearing molecules such as HC_3N would be particularly interesting. To further characterize the isotopic composition of the gas, it would also be important to search for molecules containing the ^{15}N , ^{17}O , and ^{18}O isotopes because CNO nucleosynthesis models make specific predictions for the relative abundance of these elements. Finally, it would be very interesting to characterize the spatial distribution of the molecular material in the Homunculus. Our observations suggest a source size of order $1''$, but it is clear from the composite nature of the line profiles, that observations at sub-arcsecond resolution would enable a detailed study of the spatial distribution of the molecular material and of its kinematics. ALMA will, of course, be the instrument of choice for such observations.

5. Conclusions and perspectives

In this *Letter*, we have reported the detection of six new molecules, including carbon monoxide, and two of their less abundant isotopic forms toward η Carinae. This triplicates the number of molecules known in this object. While the abundances of CO and HCO^+ are found to be standard, molecules containing nitrogen or the ^{13}C isotopic form of carbon are over-abundant by about one order of magnitude. This indicates that the material expelled by η Carinae during the Great Eruption is CNO-processed stellar matter.

Additional single-dish and interferometric observations will be very important to further characterize the chemical composition of the gas on the Homunculus, and to establish its spatial distribution. Observations of additional nitrogen bearing molecules and of species containing specific isotopes of carbon, oxygen, and nitrogen will be particularly interesting. Herschel spectroscopic observations, currently being collected, will also provide very interesting, complementary information.

We thank Arnaud Belloche, Antoine Gusdorf, and Friedrich Wyrowski for their help with the observations and data reduction. L.L., L.A.Z., and L.F.R. acknowledge the support of DGAPA, UNAM, and of CONACyT (México). LL is indebted to the Alexander von Humboldt Stiftung for financial support. This research made use of the myXCLASS program (<https://www.astro.uni-koeln.de/projects/schilke/XCLASS>), which accesses the CDMS (<http://www.cdms.de>) and JPL (<http://spec.jpl.nasa.gov>) molecular data bases.

REFERENCES

- Allen, D. A., & Hillier, D. J. 1993, *Proceedings of the Astronomical Society of Australia*, 10, 338
- Cappa, C. E., Rubio, M., & Goss, W. M. 2001, *AJ*, 121, 2664
- Comito, C., Schilke, P., Phillips, T. G., et al. 2005, *ApJS*, 156, 127
- Cox, P., & Bronfman, L. 1995, *A&A*, 299, 583
- Davidson, K., Dufour, R. J., Walborn, N. R., & Gull, T. R. 1986, *ApJ*, 305, 867
- Davidson, K., Ebbets, D., Johansson, S., et al. 1997, *AJ*, 113, 335
- Davidson, K., Walborn, N. R., & Gull, T. R. 1982, *ApJ*, 254, L47
- Dufour, R. J., Glover, T. W., Hester, J. J., et al. 1997, *Luminous Blue Variables: Massive Stars in Transition*, 120, 255
- Gomez, H. L., Vlahakis, C., Stretch, C. M., et al. 2010, *MNRAS*, 401, L48
- Güsten, R., Nyman, L. Å., Schilke, P., et al. 2006, *A&A*, 454, L13
- Güsten, R., Baryshev, A., Bell, A., et al. 2008, *Proc. SPIE*, 7020,
- Heyminck, S., Kasemann, C., Güsten, R., de Lange, G., & Graf, U. U. 2006, *A&A*, 454, L21
- Hofmann, K.-H., & Weigelt, G. 1988, *A&A*, 203, L21
- Hogerheijde, M. R., van Dishoeck, E. F., Blake, G. A., & van Langevelde, H. J. 1997, *ApJ*, 489, 293
- Hillier, D. J., Davidson, K., Ishibashi, K., & Gull, T. 2001, *ApJ*, 553, 837
- Humphreys, R. M., & Davidson, K. 1999, *Eta Carinae at The Millennium*, 179, 3
- Milam, S. N., Savage, C., Brewster, M. A., Ziurys, L. M., & Wyckoff, S. 2005, *ApJ*, 634, 1126
- Neugebauer, G., & Westphal, J. A. 1968, *ApJ*, 152, L89
- Padovani, M., Walmsley, C. M., Tafalla, M., Hily-Blant, P., & Pineau Des Forêts, G. 2011, *A&A*, 534, A77
- Pulliam, R. L., Edwards, J. L., & Ziurys, L. M. 2011, *ApJ*, 743, 36

- Rizzo, J. R., Martín-Pintado, J., & Desmurs, J.-F. 2003, *A Massive Star Odyssey: From Main Sequence to Supernova*, 212, 740
- Rizzo, J. R., Martín-Pintado, J., & Henkel, C. 2001, *ApJ*, 553, L181
- Rose, W. K. 1998, *Advanced Stellar Astrophysics*, by William K. Rose, pp. 494. ISBN 0521581885. Cambridge, UK: Cambridge University Press, May 1998.
- Smith, N. 2004, *MNRAS*, 351, L15
- Smith, N., & Morse, J. A. 2004, *ApJ*, 605, 854
- Smith, N., Morse, J. A., Gull, T. R., et al. 2004, *ApJ*, 605, 405
- Smith, N. 2002, *MNRAS*, 337, 1252
- Smith, N., Brooks, K. J., Koribalski, B. S., & Bally, J. 2006, *ApJ*, 645, L41
- Smith, N. 2006, *ApJ*, 644, 1151
- van der Tak, F. F. S., Black, J. H., Schöier, F. L., Jansen, D. J., & van Dishoeck, E. F. 2007, *A&A*, 468, 627
- Vasyunina, T., Linz, H., Henning, T., et al. 2011, *A&A*, 527, A88
- Verner, E., Bruhweiler, F., Nielsen, K. E., et al. 2005, *ApJ*, 629, 1034
- Walborn, N. R. 1995, *Revista Mexicana de Astronomia y Astrofisica Conference Series*, 2, 51
- Weigelt, G., Albrecht, R., Barbieri, C., et al. 1995, *Revista Mexicana de Astronomia y Astrofisica Conference Series*, 2, 11
- Ziurys, L. M., Tenenbaum, E. D., Pulliam, R. L., Woolf, N. J., & Milam, S. N. 2009, *ApJ*, 695, 1604